Tribology International 42 (2009) 1838–1845

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

# Tensile stress fatigue life model of silicon nitride ceramic balls

J.L. Zhou [a], G.Q. Wu [a,*], W.N. Zhu [a], X.Y. Chen [b]

[a] School of Mechanical Engineering, Nantong University, Nantong 226019, China
[b] Research Institute of Bearings, Shanghai University, Shanghai 200072, China

ARTICLE INFO

*Article history:*
Received 23 August 2008
Received in revised form
12 December 2008
Accepted 15 December 2008
Available online 6 January 2009

*Keywords:*
Ceramic ball
Silicon nitride
Life prediction
Tensile stress

ABSTRACT

The RCF (rolling contact fatigue) life of ceramic balls is a reliable technique to assess whether or not they are suitable to be used in rolling bearings. The relation expression between failure probability and RCF life was deduced with Weibull fracture statistic method for the silicon nitride ceramic ball in ball–cylinder geometric model. The tensile stress life model about silicon nitride ceramic balls was set up between RCF life and contact stress on the basis of the correlative numerical solution between the rating life and the maximum contact stress. It is conceived basing on maximum principal tensile stress. The failure cause, fatigue phenomenon and mechanics of balls are analyzed. The analysis shows that considering the maximum tensile stress as fatigue failure critical stress is reasonable. It is indicated that the tensile stress life model is feasible through RCF test with different stress level. It is verified by the tensile stress life model that silicon nitride ceramic balls failed by the maximum principal tensile stress, not by the maximum shear stress. In comparison with the L–P shear stress life model, the tensile stress life model is reasonable for RCF life prediction of silicon nitride ceramic balls.



## 1. Introduction

Ceramic materials such as silicon nitride applied to rolling element bearings have many advantages over traditional bearing steels. The low density, high stiffness, good corrosion resistance, low coefficient of thermal expansion, and high temperature properties of ceramics are very desirable for their use as rolling elements. The ceramic bearings have good prospects in aerospace, military and machining domains etc. The ceramic bearings include full ceramic bearings and hybrid bearings. The former are made of ceramic material, and the latter are comprised of inner and outer rings made of bearing steel while the balls are made of ceramic.

Ceramic ball is one of the most important bearing elements. The RCF (rolling contact fatigue) life of ceramic balls is a reliable technique to assess whether or not they are suitable to be used in rolling bearings. In general, at room temperature, silicon nitride is basically more brittle than steel. The values of fracture toughness and bending strength in ceramic are lower than hardened bearing steel. It is necessary that the RCF life of ceramic balls is researched in order to ensure ceramic bearings reliability and prolong its life.

In all kinds of ceramic materials, spalling is as a major failure mode in silicon nitride as in steel material. A lot of researchers have proceeded to background research about silicon nitride [1–7]. Though lots of experiments on silicon nitride balls performance were published, studies of the RCF life model are scarce. The brittle failure of silicon nitride ceramics elements was predicted in rolling contact using fracture mechanics by Oguma [5]. The fatigue cracking failure of ceramic rolling elements under Hertzian loading was predicted by Chiu [6]. The shear stress life model of ceramic balls basing on the maximum dynamic shear stress theory was set up by Yuanke [7].

It is not convenient that the failure probability formulations, derived by Oguma [5] and Chiu [6], are used to predict RCF life of ceramic balls. The both are complex, relating to crack length parameter etc. The shear stress life model derived by Yuanke [7] is lack of credibility because it was not verified by experiment.

It is well known that life theory of steel bearings is maturity [8], and that of ceramic bearings is deficiency yet. It is difficult to apply the life model of steel balls to ceramic balls directly because of different failure mechanism.

The objectives of this work were to analyze the relation between the RCF life of silicon nitride ceramic balls and the maximum contact stress, set up the mathematical model about silicon nitride ceramic balls between RCF life and contact stress, and research the failure mechanism of ceramic balls and the life prediction method.

## 2. Calculation model

As shown in Fig. 1, while the material element has experienced due to the moving contact load, the cracks propagation form has three modes as follows: mode I, mode II, and mode III [9].

For steel bearings, the RCF life is predicted according to L–P theory. The life model was set up basing on maximum dynamic

* Corresponding author. Tel.: +8651385012075; fax: +8651385012180.
*E-mail address:* wu.gqing@163.com (G.Q. Wu).

0301-679X/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.triboint.2008.12.006

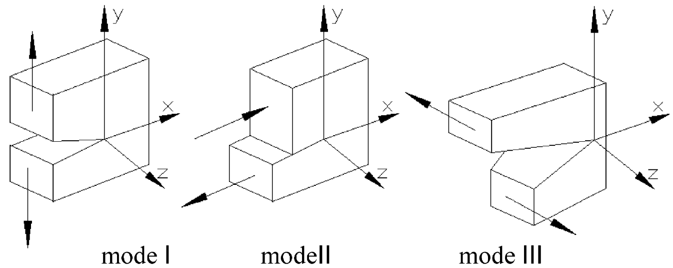


**Fig. 1.** Mode of crack surface displacement.

shear stress (mode II crack growth by shear stress shown in Fig. 1) [8].

Weibull [10] founded a statistical approach to determine the strength of solids. Weibull related the material strength to the volume of the material subjected to stress. If we imagine the solid to be divided in an arbitrary manner into $n$ volume elements, the probability of survival for the entire solid can be obtained by multiplying the individual survivabilities together as follows:

$$S = S_1 \cdot S_2 \cdots S_n \tag{1}$$

where the probability of failure $F$ is

$$F = 1 - S \tag{2}$$

Weibull further related the probability of survival $S$, the material strength $\sigma$, and the stressed volume $V$ according to the following relation:

$$\ln \frac{1}{S} \propto \int_V f(X)\,\mathrm{d}V \tag{3}$$

The tensile strength of ceramic materials was weak. The reason was that defects and inhomogeneity in the ceramic materials made them were sensitive to tensile stress. The origin cracks are initiated from flaws in the ceramic material. The distribution of the flaws in the number and size are random. On the basis of Weibull theory hypotheses are as follows:

(1) The ceramic material is not homogeneous. There are volume defects in the ceramic material. Stress concentration occurs around the existing volume defects when a load applied. Under the cyclic stress, tiny cracks are formed. The cracks originating from volume defects propagate in course of running. In the end, these cracks propagate to microscopic cracking due to the cyclic stresses.
(2) The maximum principal tensile stresses play a dominant role in course of crack propagation. The RCF critical stress is maximum principal tensile stresses. The cracks propagate in mode I shown in Fig. 1 not mode II as steel.
(3) The RCF failure of ceramic materials is formed step by step. The failure is related to the number of stress cycles $N$. The more number of stress cycles $N$ are, the bigger RCF failure probability is.
(4) The RCF failure probability is related to the stressed volume $V$ for contact bodies under the action of contact load. The greater stressed volume $V$ is, the more defects are, and the bigger RCF failure probability is.
(5) The RCF failure accord with Weibull rule.

On the basis of above hypotheses, referring to Weibull [11,12] formula for steel material as follows: $f(X) = \tau^c N^e$. Where $\tau$ is the critical shear stress, $c$ the critical shear stress-life exponent, $e$ the Weibull slope, and $N$ the number of stress cycles to failure. For ceramic material

$$f(X) = \sigma^c N^e$$

so

$$\ln \frac{1}{S} \propto \int_V \sigma^c N^e\,\mathrm{d}V \tag{4}$$

the following equation can be derived:

$$F \propto 1 - \exp\left[-\int_V \sigma^c N^e\,\mathrm{d}V\right] \tag{5}$$

where $F$ is the failure probability, $\sigma$ the maximum principal tensile stress, $c$ the tensile stress-life exponent, $e$ the Weibull slope, and $N$ the number of stress cycles to failure.

## 3. Ball–cylinder contact model

In order to set up the relation between the RCF life and contact stress, the ball–cylinder model shown in Fig. 2 is chosen according to the ball bearings operating principle. In Fig. 2, $y$ is the rolling direction, $x$ is perpendicular to the rolling direction, and $z$ is in the depth direction, the origin of coordinates $O$ is the center of contact surface. According to Hertz theory, the shape of contact face is ellipse. The semi-major axis of the ellipse $a$, the semi-minor axis of the ellipse $b$ and the maximum contact stress $p_0$ are calculated, respectively, by following equations.

$$p_0 = \frac{3P}{2\pi ab} \quad a = \left(\frac{6K^2\varepsilon FR}{\pi E'}\right)^{1/3}$$

$$b = \left(\frac{6\varepsilon FR}{\pi KE'}\right)^{1/3} \quad E' = 2\Big/\left(\frac{1-\upsilon_1^2}{E_1} + \frac{1-\upsilon_2^2}{E_2}\right)$$

where $R$ is the synthesis radius of curvature, $P$ the contact load, $\varepsilon$ the first elliptical integral, $K$ the aspect ratio (equal to $a/b$), $\upsilon_1$, $\upsilon_2$ are Poisson ratio for ball and cylinder, respectively, and $E_1$, $E_2$ are Young's modulus for ball and cylinder, respectively. The physical dimensions and material parameters of ball and cylinder are listed in Table 1. The maximum contact and contact ellipse parameters are listed in Table 2.

Stress components of each point underneath contact surface are shown in Fig. 3. After acquiring stress components according to Ref. [13], the first, second and third stress invariant may be calculated by following equations:

$$I_1 = \sigma_x + \sigma_y + \sigma_z \tag{6a}$$

$$I_2 = \sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_x - (\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) \tag{6b}$$

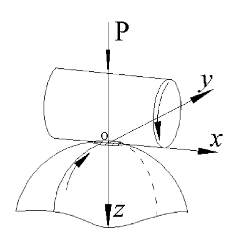


**Fig. 2.** Ball–cylinder model.

**Table 1**
Physical dimensions and material parameters of ball and cylinder.

| Contact body | Material | Physical dimension | Poisson ratio | Young's modulus (GPa) |
|---|---|---|---|---|
| Ball | $Si_3N_4$ | $\phi$12.7 | 0.26 | 310 |
| Cylinder | GCr15 | $\phi$25 | 0.3 | 206 |